A LIQUEFIER FOR MARS SURFACE PROPELLANT PRODUCTION

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ABSTRACT

NASA's planned Mars exploration missions will require that cryogenic propellants be manufactured on the surface. The present scenario calls for oxygen and methane gases to be produced using the carbon dioxide atmosphere plus seed hydrogen brought from Earth. Gases will require liquefaction for both storage on the Martian surface and for use in the ascent vehicle. The planned liquefaction rates range from 12.6 g/hr of oxygen for the 2003 robotic mission to 2500 g/hr for the later human missions.

This paper presents the results of a nitrogen liquefaction demonstration using a commercially available cryocooler. The experiment was set up to liquefy nitrogen gas instead of oxygen to limit laboratory safety concerns. A nitrogen gas condensor, attached to the cooler's cold tip, was sized to liquefy up to 42 gN,/hr at the intended storage pressure (0.2 MPa). The experiment was conducted inside an atmospheric, air-filled, refrigerated chamber simulating the average Martian daytime temperature (240 K). In this demonstration a liquefaction rate of 9.1 gN,/hr was realized, which is equivalent to 13 gO,/hr.

INTRODUCTION

NASA is planning an extensive set of exploration missions. Prominent in this set of missions is a series of human missions to Mars. These missions plan to make extensive use of cryogenic propellants, some of which will be manufactured on Mars[1]. This In-Situ-Consumable-Production (ISCP) is part of the scheme to reduce the mass launched from Earth through In-Situ-Resource-Utilization (ISRU). Maintaining propellants on Mars requires liquefaction, storage, and transfer of cryogens on Mars. Some of the proposed chemical processes for ISCP require hydrogen as feed stock. The hydrogen will be transported from Earth as a liquid. The oxygen is to be manufactured on location by ISCP.

One of the goals of the planned 2003 mission to Mars is to demonstrate that oxygen gas produced on its surface can be liquefied at a rate of 12.6 g/hr and stored at 2 atm pressure (0.2 MPa). The liquefier will run for 60 days, roughly 8-12 hours each day, while being exposed to a typical daytime Mars surface temperature of 240 K. The present paper demonstrates that the planned 2003 liquefier requirement can be met with existing, off-the-shelf hardware. The following discusses our test apparatus, the dimensioning of the condensor used in liquefaction and the experimental results.
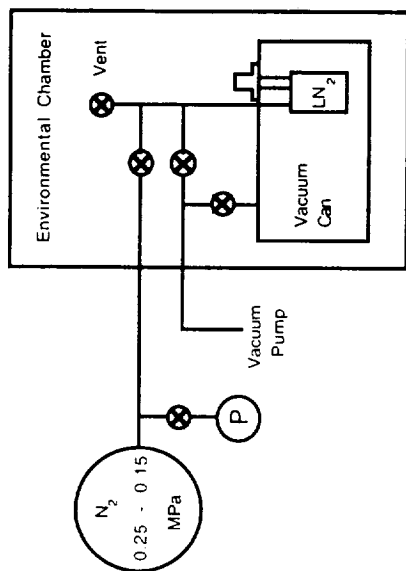
Figure 1. Schematic of the test setup.

EXPERIMENTAL SETUP AND PROCEDURE

A schematic of the experimental setup is shown in Figure 1. The liquefier consists of a cryocooler and a condensor (copper) that is epoxied directly to the cryocooler cold tip. The cooler selected is an off-the-shelf BEI 1000E cooler. The liquefier is mounted on a small Dewar which is merely used as a vacuum can. The assembly is placed inside an environmental chamber. The chamber contains refrigerated air (245 K) at atmospheric pressure that is circulated by means of a fan. The nitrogen gas that is to be condensed is stored outside the chamber in a 36.7 L sphere at 0.2 MPa pressure and 293 K. A gas handling system allows evacuation of the apparatus and pressurization of the condensor as required. The condensor is pressurized through a 4.8 mm (3/16''; inner diameter) stainless steel fill tube. The assembly, as placed in the environmental chamber, is shown in Figure 2. The liquefier, as mounted on the Dewar top flange, is shown in Figure 3.
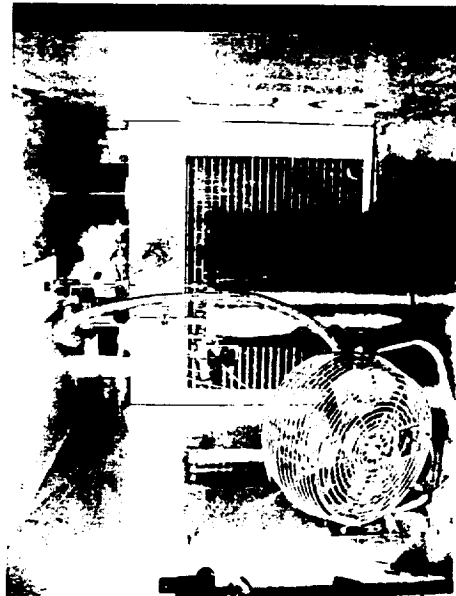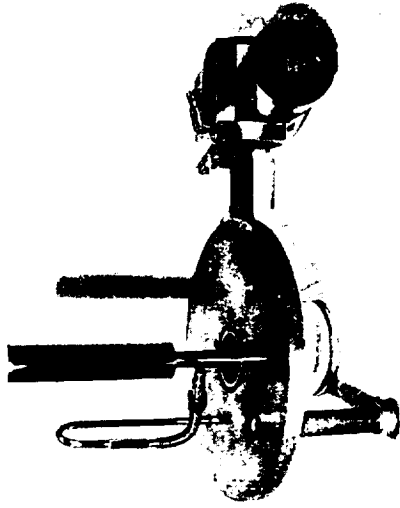
Figure 3. The liquefier (shown upside down).

The liquefaction procedure is as follows. The storage sphere is pumped, purged and pressurized with dry nitrogen gas and then is valved off. The Dewar and condensor are pumped out before and during cooldown of the environmental chamber. Once the chamber and the apparatus have cooled down to near Martian temperature (245 K) the cryocooler is turned on. A silicon diode thermometer attached to the condensor is used to monitor its temperature. When the condensor reaches the liquefaction temperature (85 K) valves are opened allowing gas to flow from the sphere to the condensor as liquefaction occurs. Measuring the pressure drop in the sphere versus time, the mass transfer rate, i.e. the liquefaction rate, is derived.

Minor issues concerning the test procedure are the following. As for selecting to liquefy nitrogen rather than oxygen in this demonstration, nitrogen has the obvious advantage in safety. Further, demonstrating that the liquefier is suitable for nitrogen provides only greater assurance that it is appropriate for oxygen liquefaction since oxygen has a higher boiling point. In terms of quantities liquefied at the same heat load to the cooler, roughly 1.3 gLO$_2$ corresponds to 1 gLN$_2$. Lastly, the environmental chamber has been run at 245 K rather than the average Mars temperature of 240 K in order to stay within the operating margin of the various rubber vacuum seals. Replacement of all vacuum seals by other materials has not been pursued considering the benefit gained for this test would be minor.

CONDENSOR

In order to achieve the maximum liquefaction rate the condensor must have sufficient internal surface area for condensation. Insufficient surface area will result in under-utilization of the available cooling power. We will assume that the cooler provides cooling only at the cold tip, i.e. all the enthalpy associated with gas cooldown and liquefaction is rejected at the condensor attached to the cryocooler cold tip. Thus, the effective heat load is:

$$Q_1 = \left[h_{fg} + \Delta h_g \right] \dot{m} \qquad (1)$$

(symbols are defined in the nomenclature at the end of this paper).

In terms of the average conductance at the wall Eqn. (1) becomes:

$$\dot{Q}_1 = h \, A \, \delta T \qquad (2)$$

In our tests the condensor consists of a cylindrical copper can. For this case, laminar film condensation on a vertical plate applies. The conductance at the condensor wall is a function of the mass flow rate, latent heat and enthalpy of the gas, the condensation surface area and the temperature difference (subcooling) between the exchanger and the liquid. The applicable correlation is[?]:

$$h = 0.943 \left[g \, \rho_p \left(\rho_p - \rho_v \right) k^3 h_{lg} / L \, \mu_p \, \delta T \right]^{1/4} \qquad (3)$$

Although the available refrigeration capacity of the cooler allows only a liquefaction rate of roughly 10 g/hr, the condensor has been sized according to the equations stated above for a maximum liquefaction rate of 30 gN₂/hr. The condensor is constructed of a copper can of 41.4 cm³ total volume and 79.3 cm³ inside surface area, containing a tube heat exchanger of 26.6 cm³ surface area suspended from the can's top. The total condensor surface area is 106 cm³.

RESULTS AND DISCUSSION

Preceding both liquefaction and load testing the cooler has been run establishing the no-load cold tip temperature for the conditions in the environmental chamber (245 K). A no-load temperature of 46±1 K has been measured. After the no-load bottom temperature is reached and before liquefaction, the cooler is turned off temporarily until the condensor temperature rises above 70 K. By this measure solidification of nitrogen in the fill line is avoided. Then when the condensor is pressurized, the storage vessel pressure begins to drop and the condensor temperature is observed to rise and to stabilize at roughly 85 K. The fall in pressure is monitored over time. Converting the pressure data to mass flow and liquefaction rate, results in an average liquefaction rate of approximately 9.1 gN₂/hr over a 3.55 hour period. The liquefaction rate versus time is shown in graphical form in Figure 4.
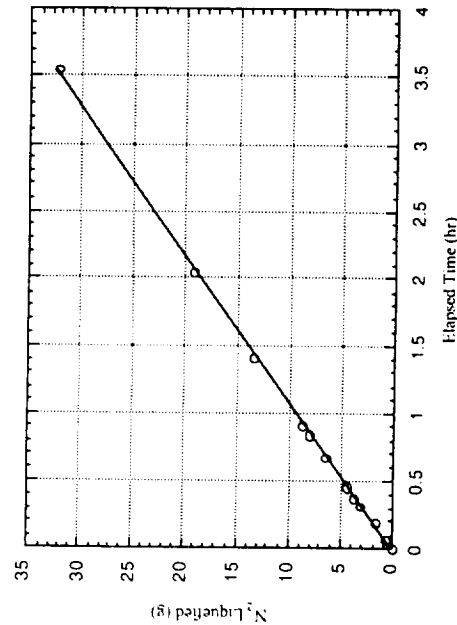

Figure 4. N₂ liquefaction versus time.

The oxygen liquefaction rate equivalent to the nitrogen liquefaction rate is derived in the following manner. The nitrogen liquefaction rate of 9.1 g/hr was achieved at 85 K. The cooler manufacturer's data show a 33% increase in refrigeration capacity at 97 K over that at 85 K (97 K is the 0.2 MPa liquefaction temperature of oxygen). Also to be taken into account is the ratio between the total enthalpy changes of oxygen and nitrogen when cooled from 293 K and liquefied at their respective liquefaction temperatures (400 J/gO₂ and 426 J/gN₂). It follows that liquefying nitrogen at a rate of 9.1 gN₂/hr corresponds to an oxygen liquefaction rate of 12.9 gO₂/hr. This exceeds the planned 2003 Mars mission goal of 12.6 gO₂/hr by 2 %.

Two load tests on the cooler, with the condensor pumped out, have been performed. At 0.1 W the condensor temperature stabilized at 48.5 K; at 1.18 W the condensor temperature stabilized at 85 K. The cooling power measurement at 85 K was made in order to verify the cooling power exerted by the cryocooler when it is liquefying nitrogen gas at 85 K. The measured cooling power should agree with the heat load to the cooler as expressed in Eqn. (1). From the enthalpy change (426 J/gN₂) and the measured mass flow the heat load is calculated to have been 1.08 W during liquefaction. Considering the close agreement of the measured cooler power during the load test and the heat load required for liquefaction, it should be noted that the limiting factor for the liquefaction rate was the cooler power and not the size of the condensor. As previously stated, the system was sized for up to 42 g/hr liquefaction.

An analysis was performed to calculate the parasitic heat input to the cooler due to both conduction and radiation from the 245 K environment to the condensor at 85 K. The radiation heat input through three layers of aluminized mylar was estimated to be on the order of 0.10 W. The conduction along the stainless steel nitrogen fill tube was calculated as 0.070 W. The conduction along the instrumentation wires was calculated to be 0.019 W. All this adds up to a total parasitic heat input of about 0.19 W.

CONCLUSIONS

In summary, it has been demonstrated that oxygen liquefaction rates of the planned 2003 Mars mission can be met with existing off-the-shelf hardware. Future work will focus on the more formidable challenge of demonstrating that the 2500 g/hr requirement for the later human missions can be met with an economically feasible package.

REFERENCES

1. Salerno, L. J., and Kittel, P., Cryogenics and the Human Exploration of Mars, Cryogenics (in process)
2. Kreith, F., "Principles of Heat Transfer", 3rd Ed., Intext Press, NY (1973), p. 527

NOMENCLATURE

A	surface area	Q_l	liquefier load
g	gravitational acceleration	T_c	cold temperature
h	conductance	T_h	hot temperature
h_{fg}	latent heat of condensation	μ	dynamic viscosity
h_g	enthalpy of gas	δT	subcooling of condensor
k	thermal conductivity of liquid	ρ_v	density of gas
l	fin length of liquefier	ρ_p	density of propellant